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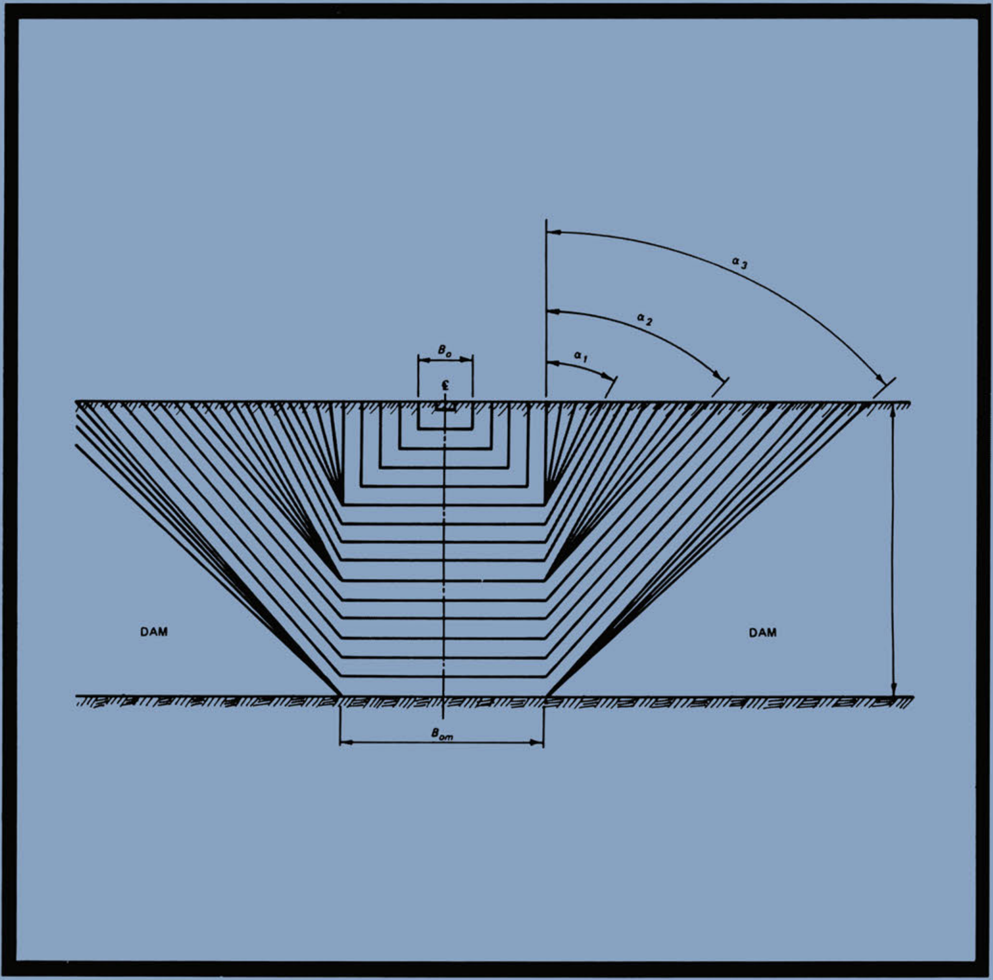
DAM BREACH MODELING TECHNOLOGY

by

Vijay P. Singh



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To

Anita,

Vinay, and

Arti

Contents

Preface

Dams are constructed for economic development, and their construction involves large investments of money, and natural and human resources. Of the various types of dams constructed around the globe, earth dams are the most common type and constitute the vast majority of dams. When a dam fails, it culminates in the sudden release of artificially stored water which, in turn, becomes a potential menace to virtually everything downstream. The dam failure may result in loss of life and property. In recent years, instances of dam failure in the world have been too many, and the resulting loss too high. As a result, dam safety programs have been developed in most countries of the world since the beginning of the nineteenth eighties.

Earth dams are more susceptible to failure than other types. The cause of failure is often either overtopping or piping. The modeling of dam breaching due to either or both of these causes is of fundamental importance to development of dam-safety programs. This book is, therefore, an attempt to present some aspects of earth-dam breach modeling technology. It is hoped that others will be stimulated to write more comprehensive texts on this subject of growing interest and importance.

The book is divided into eight chapters. The first chapter is introductory and discusses some aspects of dams and dam failures in the world. Dam breaching, including the types and causes of dam failures, and mechanics of breach erosion, is presented in Chapter 2. Hydraulics of dam breaching constitutes the subject matter of Chapter 3. It encompasses some aspects of flood hydrology and reservoir hydraulics, hydraulics of flow over the dam, erosion and sedimentation, geomechanics of breach slope collapsing, hydraulics of channels and floodplains, damage assessment, and disaster mitigation. Calibration and verification of models require data. Laboratory data on dam breaching is virtually nonexistent. Due to the almost instantaneous nature (or very short time) of failure, field data are extremely limited and are, in most cases, after the dam has been breached for the most part. However limited the field data are, they are nevertheless useful. These data, assembled from various sources, are presented in Chapter 4. The technology of dam breaching is far from advanced and is still in the early stages. Simple empirical and conceptual models are often useful and seem to provide, under certain conditions, satisfactory results. Such models are derived in dimensional form in Chapter 5 and in dimensionless form in Chapter 6. More detailed mathematical models are reviewed in Chapter 7. These models portray the evolution in breach-modeling technology and the state-of -art. A short comparative evaluation of these models and an assessment of dam-breach modeling technology are presented in Chapter 8. The evaluation is based upon model components and their parameters, and input data requirements as well as initial conditions, whereas the assessment encompasses accomplishments, unresolved problems, and suggestions for further work.

The author expresses his appreciation to his wife, Anita, who did the drafting of many of the figures. His son, Vinay, and daughter, Arti, proofread part of the text. His brothers and sisters, who reside in India, offered moral support and encouragement, and were more than willing to aid, especially in the time of need. Anita, Vinay, and Arti allowed him to work extra hours during evenings, weekends, and holidays, without complaining and demanding. The author is deeply grateful to all of these family members for their love, support, and sacrifice, without which this book would not have been completed.

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CHAPTER 1

Introduction

Dams have been a vital part of human civilization. History has amply documented close association of dams with the rise and fall of civilizations, especially those highly dependent on irrigation. High dams, impounding large volumes of water, have been and continue to be constructed on the rivers around the world for hydro-electric power generation, flood control, irrigation, water supply, navigation, recreation, and other purposes. Furthermore, large embankments have inherent ability to accommodate a broader range of site conditions than would be suitable for more rigid dams (Jansen, 1988).

The benefit of dams to mankind is unquestionable. Their earliest role was to provide storage of water for irrigation which was vital for agricultural production in many countries. Then, the role expanded to providing water for transport, industrial processes, and the growing cities. In the 18th Century, dams were constructed to store water for canals; during 19th Century, the majority of dams were built for water supply as well; and early in the 20th Century, they were for hydropower generation as well.

Schnitter (1967) has documented an excellent short history of dam engineering and provided location of some historical dams up to the end of the 18th century as shown in Figure 1.1. Historical evidence points that some of the earliest dams were constructed around 4000 years B.C. The oldest dam in the world (Kerisel, 1985) was built of earth with a masonry facing at Jawa in Jordan around 4000 B.C. Remnants of Saddel-Kafara Dam, in the Wadi el-Garawi near Helwan in Egypt, date back to 2600 B.C. to 2900 B.C. It was a 46-foot (14-meter) high rockfill with cut-stone masonry faces and a core of rubble and gravel. The dam is reported to have lost its central section to flood soon after or in the final stages of its construction. According to Takase (1967), around the second and third centuries many earth dams had already been constructed in Japan primarily for irrigation water supply, and in the eighth century, a large dam over 20 m in height, had been built. More than 10,000 earth dams are several hundred years old and are still in use for rice-paddy irrigation.

The Romans constructed many dams of mortared masonry, some of which are still in use. Perhaps the oldest surviving arch dam is the dam built in a narrow gorge on the Kebar River, around 1300 A.D., about 15 miles (24 km) south of the town of Qum in the Mongol period in now Iran. It is about 85 foot (26 meter) high

1.Kosheish(about 2900 B.C.) and Sadd-el-Kafara(about 2500 B.C.)
2.Mashkai and Lakorian(around 2000 B.C.)
3.Homs(about 1300 B.C.)
4.Sudd-al-Arim(about 750 B.C.)
5.Ajilah,Qayin and Bavian(about 700 B.C.)
6.Basawakkulam(about 430 B.C.) and later Sinhalese Dams
7.Sudarsana(about 300 B.C.)
8.Gukow(about 240 B.C.)
9.Siq and Kurnub(about Christ)
10.Cornalbo, Proserpina and Esparragalejo (1st Century)
11.Dams near Homs(Roman)
12.Orukaya(Roman)
13.Cavdarhisar(Roman)
14.Al-Harbaqa(Roman)
15.Kaerumataike(162) and Daimonike(1128)
16.Shadhorvan(about 270)
17.Dara(about 550)
18.Moti Talav(10th Century)
19.Bhojpur(11th Century)
20.Almonacid(11th Century)
21.Kebar and Saveh(14th Century)
22.Cento(1450)
23.Spiegelfreudersee(1460)
24.Tibi(1589) and Elche(1590)
25.Ming(16/17th Century)
26.Ikinci(1651)
27.St. Ferreol(1675)
28.Oderteich(1721)
29.Pabellon, Los Arcos and San Jose de Guadalupe(18th Century)
30.San Diego and Los Angeles(18th Century)

Fig. 1.1. Location of some historical dams listed chronologically up to the end of the 18th century (after Schnitter, 1967).

and 180 feet (55 meter) long, and is composed of cemented rubble masonry with mortared stone block facing, with the arch keyed into the canyon walls. In 1747, a buttress dam, Albuera de Feria Dam, near Badejoz in Spain was constructed out of rubble masonry. It is 77-foot (23.5 meter) high and 558 foot (170 meter) long, with buttresses supporting its downstream face. In India there was a tradition of dam building (Rao, 1951), and many dams were constructed by traditional methods in eighteenth and nineteenth centuries. Perhaps the first multiple-arch dam, called Meer Allum, was constructed out of masonry in 1800 near Hyderabad, India. It is about 40 foot (12-meter) high and 2500 feet (762 meter) long.

Many dams were constructed in the nineteenth century in Europe, North America and elsewhere, as shown in Table 1.1. The advent of heavy machinery altered the art and engineering of dam construction in the twentieth century, as evidenced by the construction of the Salt Springs Dam in 1931 in California in the United States of America (U.S.A.). It is a rockfill construction with a height of 328 feet (100 meters). Earth-cored rockfill dams began to gain popularity in the 1940s, and concrete-faced compacted rockfills in 1960s. The heavy machinery permitted construction of dams of increasing height. A historical development of dam heights is depicted in Table 1.2. Setting world records for rockfills are Esmeralda (Chivor) Dam 777 foot (237 meter) high built in 1975 in Columbia, and Chicoasen Dam 856 foot (261 meter) high constructed in 1980 in Mexico. The world's highest embankment dam exceeded 100 m in height in 1926, 200 m in 1968, and 300 m in 1981. In the last three decades the most notable earthfill dams of increasing size with outer zones of gravel are the 754 foot (230 meter) Oroville constructed in 1968 in the United States, the 794 foot (242 meter) Mica built in 1973 in Canada, and the 984 foot (300 meter) Nurek built in 1980 in the former Soviet Union (now Russia). Two projected embankment dams in India are Tehri, 261 m, and Kishan, 253 m. both in Uttar Pradesh, and both are expected to be completed in the 1990s. Rogun, the 335 m embankment dam in Russia, when completed, will be the world's highest dam.

Table 1.1. Dams more than 15 m high built in Western Europe and the United States (after Schnitter, 1967)

Decade	Number of dams	
	Western Europe	U.S.A.
1900–1909	90	100
1910–1919	70	220
1920–1929	170	280
1930–1939	180	280
1940–1949	180	240
1950–1959	510	530
Totals	1,200	1,650

Table 1.2. Development of dam heights historically (after Schnitter, 1967)

Masonry (Concrete) Dams			Earth (Rock) Dams		
		m			m
ca. 3000 B.C.	Kosheish (Egypt)	15	ca. 240 B.C.	Gukow (China)	
			1128 A.D.	Daimonike (Japan)	30
11th cent. A.D.	Almonocid (Spain)	29	ca. 1500	Mudduck Masur (India)	32
1158	Tibi (Spain)	46	1675	St. Ferreol (France)	36
1866	Gouffre d'Enfer (France)	60	1840	Entwistle (England)	
1904	Cheeseman (USA)	72	1867	Maday (India)	44
1905	New Croton (USA)	91	1892	San Leandro (USA)	47
1910	Shoshone (USA)	99	1909	Nexaca (Mexico)	56
1915	Arrowrock (USA)	107	1911	Bull Corral (USA)	73
1924	Schrah (Switzerland)	111	1924	Dix River (USA)	84
1929	Diablo (USA)	119	1931	Salt Springs (USA)	100
1932	Owyhee (USA)	127	1939	San Gabriel (USA)	115
1934	Chambon (France)	136	1948	Mud Mountain (USA)	130
1936	Hoover (USA)	221	1950	Anderson Ranch (USA)	139
1958	Mauvoisin (Switzerland)	237	1958	Swift (USA)	156
1961	Vaiont (Italy)	262			
1962	Grande Dixence (Switzerland)	284			

Not taken into consideration: Gasco (Spain), which was abandoned in 1789 at 57 m height due to heavy flood damage, and Puentes (Spain), which was completed to a height of 52 m in 1791, but failed in 1802 and was rebuilt only in 1884.

Not taken into consideration: Ponthook (USA), which reached 84 m height in 1887 but has a crest length of only 4 m.

1.1. Types of Dams

Dams are classified in different ways, depending upon the (1) size, (2) materials used for construction, (3) form, (4) purpose, (5) hazard potential, and so on. The first three are the most common types of classification. Table 1.3 lists two types of classifications. According to size, a dam may be small, medium, or large. The size is usually measured in terms of height or volume of water stored. In general, dams 30 meters high or more are considered large ($\geqslant 6,250$ hectare meter storage capacity), those between 12 and 30 meters high medium (between 125 and 6,250 hectare meter capacity), and those 11 meters high or less and greater than or equal to 8 meters (between 6 and 125 ha-m storage capacity) small.

Based on the materials used in construction, a dam may be homogeneous or zoned earthfill, rockfill with earth core or concrete face or concrete that depends upon gravity, arch, or buttress resistance. Some dams are constructed with a combination of materials, including earthfill, rockfill, masonry, and concrete. Some even contain timber, asphaltic, or synthetic membranes. Dams supported by buttresses are further grouped as flat-slab, multiple-arch, or massive-head.

Factors governing the suitability of a particular dam type are primarily topographic and geologic characteristics. These affect the load distribution on the foundation and the seepage field through the reservoir margins. Each kind of dam possesses distinctive features, and has merits and demerits for a particular site. Nevertheless, a careful evaluation of its suitability is to be undertaken.

Earth embankments can withstand substantial movement but have relatively low resistance to overflow. They are prone to develop differential settlement at steep abutments and at structural interfaces. Deformation of fill at these locations may result in seepage. On the other hand, concrete dams can withstand overtopping for

Table 1.3. Classification of hazard potential

Category	Height of dam (ft)	Impoundment (ac-ft)
Size of dam		
Small	25 to 40	50 to 1,000
Intermediate	40 to 100	1,000 to 50,000
Large	over 100	over 50,000
Category	**Loss of life (Extent of development)**	**Economic loss**
Hazard potential		
Low	None expected (no permanent structures for human habitation)	Minimal (undeveloped to occasional structure or agriculture)
Significant	Few (no urban development and no more than a small number of inhabitable structures)	Appreciable (notable agriculture, industry, or structures)
High	More than few	Excessive (extensive community, industry, or agriculture)

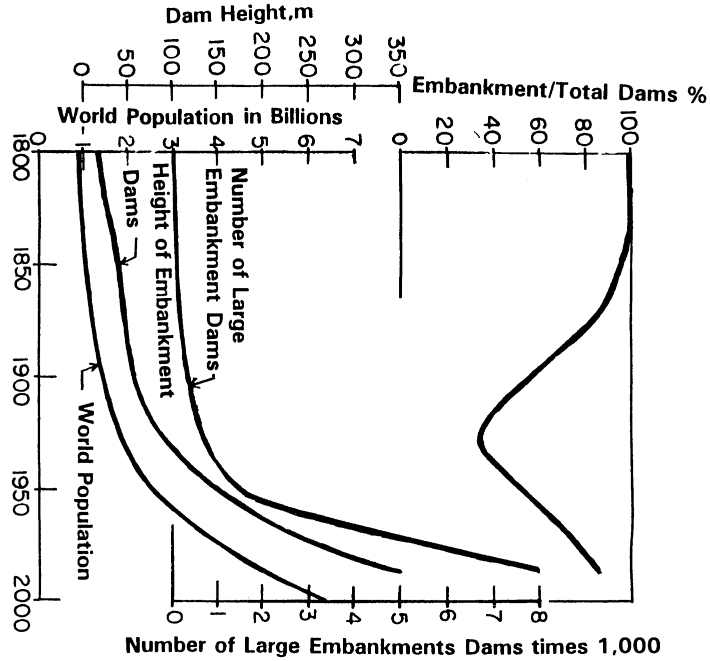

Fig. 1.2. Statistics of embankment dams during 1800–1985 (after Penman, 1986).

several hours, but their safety rests on the resistance of the foundation to impact of the spill. Arch dams can bear large loads but their integrity is a function of the strength of the abutments. Gravity dams are durable and can survive considerable weathering and site deficiencies, but their durability is undermined by the susceptibility of the foundation elements to sliding.

Prior to 1800, almost all of the world's dams were of the embankment type. In the 19th century, concrete dams gained a lot of popularity, primarily due to advances in concrete technology and structural analysis. By the turn of the century, there were, as a result, more concrete dams than large embankment dams built. In fact, in the late 1920s the ratio of embankment dams to total number of dams built dipped to its lowest value of 33%, as shown in Figure 1.2 (Penman, 1986). However, of all the large dams built recently, more than 80% are of the embankment type.

1.2. Dams in the World

The 1985 edition of world register prepared by ICOLD contains information on the number, type, and size of dams and reservoirs from 116 countries. In general, dams exceeding 15 meters in height have been included in the register. However, for four countries, including China, India, Japan, and U.S.A., each with more than 1000 dams, only those exceeding 30 meters in height have been included. Thus, a large number of small dams have been excluded from the register. Many of these dams are embankment type. For example, Britain is reported to have 411 embankment dams and 125 of other types of dams, whereas more than 2000 are subject to the Reservoirs (Safety Provisions) Act of 1930 in the country. The height of a dam in the world register has been measured from the lowest foundation rather than from the stream bed level.

With the aforementioned limitations, the number of large embankment dams is plotted against time during the period 1800–1985 in Figure 1.2 (Penman, 1986). Also plotted are the dam height, the ratio of the number of embankment dams to the total number of dams, as well as the world population. Since 1955, the number of large embankment dams has been growing at an about constant rate of 200 per year. This increase can be ascribed to the accelerating growth of world population.

In 1989, Central Water Commission of India reported that there were 3204 large dams in India out of which 473 were under construction. According to Biedermann (1985) there are 182 dams in Switzerland under the supervision of the Confederation. Of these, 44 dams are less than 15 m in height, 25 are higher than 100 m and 4 are even higher than 200 m. The highest dam in Switzerland is the 285 m high Grande Dixence Dam completed in 1961. It is still the world's highest concrete dam.

According to a survey conducted by the Japanese Ministry of Agriculture and Forestry, as of 1955 irrigation dams in Japan were as many as 276,971 with a total storage capacity of $2,149,56 \times 10^6$ m^3 which averages out to be approximately 7,800 m^3/dam.

Based on the data from 1973 edition of World Register of Dams (USCOLD, 1975), 4,918 major dams of all types were in existence in the United States. An additional 56 major dams were identified that were not included in the World Register, giving a combined total of 4,974 major dams. Except the cases having features of special interest, the Register is limited to dams in excess of 15 m in height or to those between 10 and 15 m in height if the volume of water stored exceeds 100,000 m^3. The U.S. Army Corps of Engineers (1975) identified nearly 20,000 dams in the United States as potentially dangerous in the event of a failure. According to Gruner (1967), the total number of dams in the world which might cause serious damage in the event of failure may well exceed 150,000.

The total number of dams of all types in operation in the United States corresponding to the end of each decade is shown in Figure 1.3. Also shown in the figure is similar data on only earth dams. The rate of dam construction reached a peak of 1900 per decade in 1960–69. Clearly, of the various types of dams in operation, the earth dams are the most common and constitute the vast majority of 3,604 (73%). The remaining 27% of the dams are gravity, arch, earth-rockfill and other types as shown in Figure 1.4.

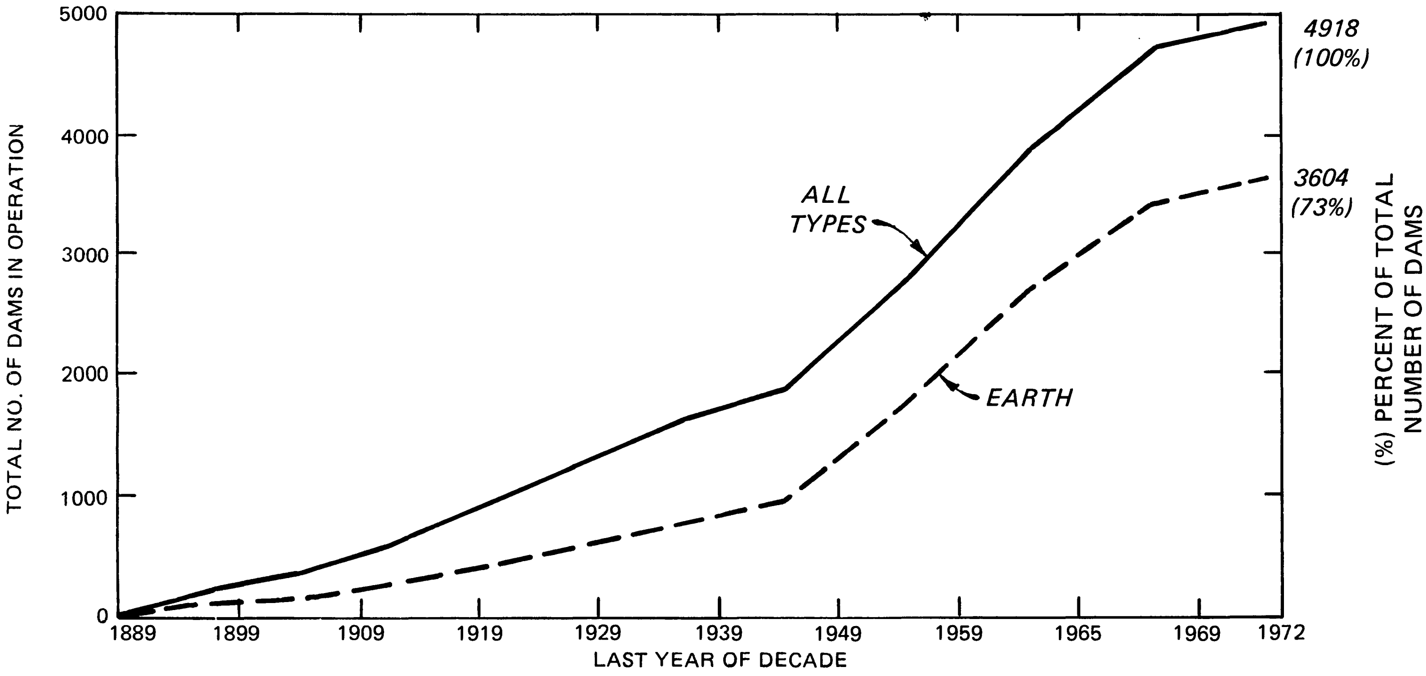

Fig. 1.3. Total number of dams in the United States versus time expressed as decades.

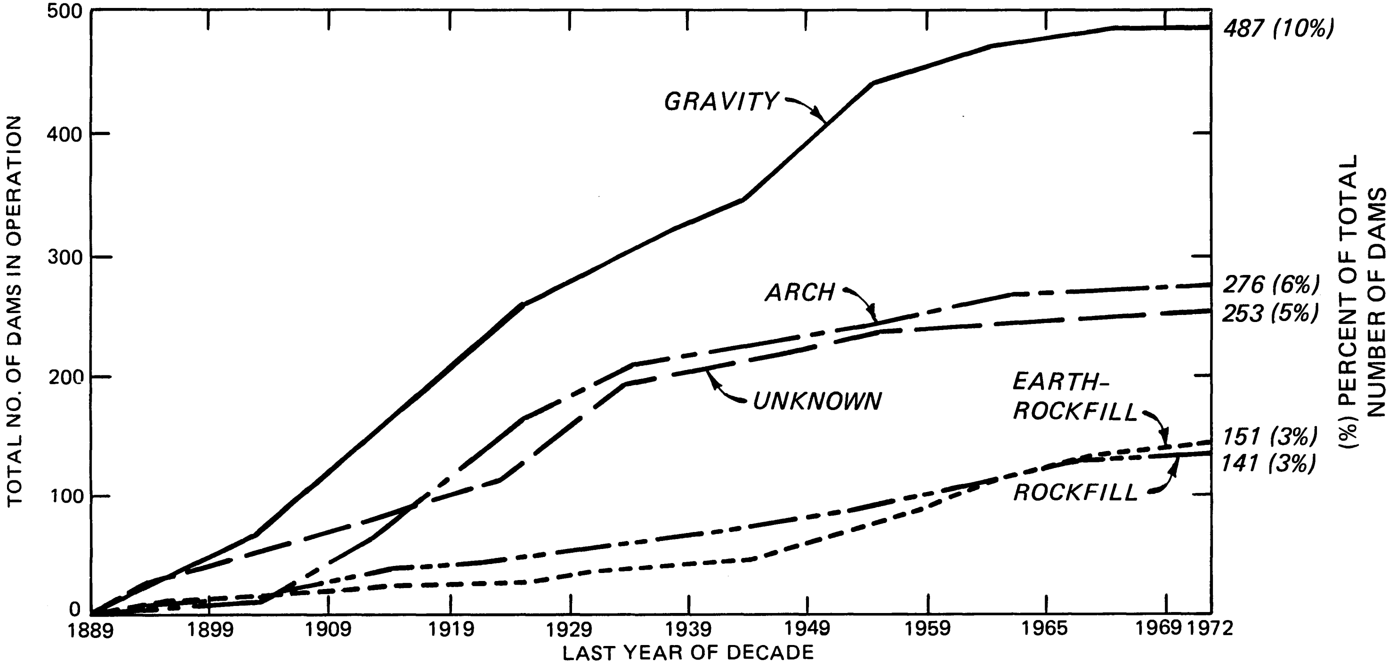

Fig. 1.4. Total number of dams of different types in the United States versus time expressed as decades.